FORM PTO-1390 (REV. 12-2001) U S DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE

TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 U.S.C. 371

ATTORNEY 'S DOCKET NUMBER: N8323-EAS

U S. APPLICATION NO (If known, see 37 CFR 1.5): 10/088441

INTERNATIONAL APPLICATION NO.	INTERNATIONAL FILING DATE	PRIORITY DATE CLAIMED
PCT/US00/40921	18 September 2000	17 September 1999

TITLE OF INVENTION: THERMODYNAMIC ENERGY CONVERSION DEVICES AND METHODS USING A DIAMOND-BASED ELECTRON EMITTER

APPLICANT(S) FOR DO/EO/US: Timothy S. Fisher; Alvin M. Strauss; Jimmy Lee Davidson; Weng Poo Kang

Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:

1. [X] This is a **FIRST** submission of items concerning a filing under 35 U.S.C. 371.
2. [ ] This is a **SECOND** or **SUBSEQUENT** submission of items concerning a filing under 35 U.S.C. 371.
3. [ ] This is an express request to begin national examination procedures (35 U.S.C. 371(f)). The submission must include items (5), (6), (9) and (21) indicated below.
4. [ ] The US has been elected by the expiration of 19 months from the priority date (Article 31).
5. [X] A copy of the International Application as filed (35 U.S.C. 371(c)(2))
   a. [ ] is attached hereto (required only if not communicated by the International Bureau).
   b. [ ] has been communicated by the International Bureau.
   c. [X] is not required, as the application was filed in the United States Receiving Office (RO/US).
6. [ ] An English language translation of the International Application as filed (35 U S.C. 371(c)(2)).
   a [ ] is attached hereto
   b. [ ] has been previously submitted under 35 U.S.C. 154(d)(4).
7. [X] Amendments to the claims of the International Aplication under PCT Article 19 (35 U.S.C. 371(c)(3))
   a [ ] are attached hereto (required only if not communicated by the International Bureau).
   b. [ ] have been communicated by the International Bureau.
   c. [ ] have not been made; however, the time limit for making such amendments has NOT expired.
   d. [X] have not been made and will not be made.
8. [ ] An English language translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371 (c)(3)).
9. [ ] An oath or declaration of the inventor(s) (35 U.S.C. 371(c)(4)).
10. [ ] An English lanugage translation of the annexes of the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371(c)(5)).

Items 11 to 20 below concern document(s) or information included:

11. [ ] An Information Disclosure Statement under 37 CFR 1.97 and 1.98.
12. [ ] An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.
13. [X] A FIRST preliminary amendment.
14. [ ] A SECOND or SUBSEQUENT preliminary amendment.
15. [ ] A substitute specification.
16. [ ] A change of power of attorney and/or address letter.
17. [ ] A computer-readable form of the sequence listing in accordance with PCT Rule 13ter.2 and 35 U.S.C. 1.821 - 1.825.
18. [ ] A second copy of the published international application under 35 U.S.C. 154(d)(4).
19. [ ] A second copy of the English language translation of the international application under 35 U.S.C. 154(d)(4).
20. [ ] Other items or information:

JC13 Rec'd PCT/PTO 15 MAR 2002

U S APPLICATION NO (if known, see 37 CFR 1.5)	INTERNATIONAL APPLICATION NO	ATTORNEY'S DOCKET NUMBER
10/088441	PCT/US00/40921	N8323-FAS

21. [X] The following fees are submitted:	CALCULATIONS PTO USE ONLY	
BASIC NATIONAL FEE (37 CFR 1.492 (a) (1) - (5)):		
Neither international preliminary examination fee (37 CFR 1.482) nor international search fee (37 CFR 1.445(a)(2)) paid to USPTO and International Search Report not prepared by the EPO or JPO **$1040.00**		
International preliminary examination fee (37 CFR 1.482) not paid to USPTO but International Search Report prepared by the EPO or JPO **$890.00**		
International preliminary examination fee (37 CFR 1.482) not paid to USPTO but international search fee (37 CFR 1.445(a)(2)) paid to USPTO **$740.00**		
International preliminary examination fee (37 CFR 1.482) paid to USPTO but all claims did not satisfy provisions of PCT Article 33(1)-(4) **$710.00**		
International preliminary examination fee (37 CFR 1.482) paid to USPTO and all claims satisfied provisions of PCT Article 33(1)-(4) **$100.00**		
ENTER APPROPRIATE BASIC FEE AMOUNT =	$ 710.00	
Surcharge of **$130.00** for furnishing the oath or declaration later than [ ] 20 [ ] 30 months from the earliest claimed priority date (37 CFR 1.492(e)).	$	

CLAIMS	NUMBER FILED	NUMBER EXTRA	RATE		
Total claims	29 - 20 =	9	x **$18.00**	$ 162.00	
Independent claims	8 - 3 =	5	x **$84.00**	$ 420.00	
MULTIPLE DEPENDENT CLAIM(S) (if applicable)			+ **$280.00**	$	
TOTAL OF ABOVE CALCULATIONS =				$ 1292.00	
[X] Applicant claims small entity status. See 37 CFR 1.27. The fees indicated above are reduced by 1/2.			+	$ (646)	
SUBTOTAL =				$ 646.00	
Processing fee of **$130.00** for furnishing the English translation later than [ ] 20 [ ] 30 months from the earliest claimed priority date (37 CFR 1.492(f)).				$	
TOTAL NATIONAL FEE =				$ 646.00	
Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31). **$40.00** per property +				$	
TOTAL FEES ENCLOSED =				$ 646.00	
				Amount to be refunded:	$
				charged:	$

a. [X] A check in the amount of $ 646.00 to cover the above fees is enclosed

b. [ ] Please charge my Deposit Account No. _____ in the amount of $ _____ to cover the above fees. A duplicate copy of this sheet is enclosed.

c. [X] The Commissioner is hereby authorized to charge any additional fees which may be required, or credit any overpayment to Deposit Account No. 23-0035 . A duplicate copy of this sheet is enclosed.

d. [ ] Fees are to be charged to a credit card. **WARNING:** Information on this form may become public. **Credit card information should not be included on this form.** Provide credit card information and authorization on PTO-2038.

NOTE: Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137 (a) or (b)) must be filed and granted to restore the application to pending status.

SEND ALL CORRESPONDENCE TO.

Emily A. Shouse
Waddey & Patterson
414 Union Street, Suite 2020
Nashville, TN 37219

SIGNATURE

Emily A. Shouse
NAME

44,336
REGISTRATION NUMBER

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant:	Fisher, et al
Serial No.:	Not yet assigned
Filed:	Not yet assigned
For:	Thermodynamic Energy Conversion Devices And Methods Using A Diamond-Based Electron Emitter
Group Art Unit:	Not yet assigned
Examiner:	Not yet assigned
Attorney's Docket No.	N8323-EAS

PRELIMINARY AMENDMENT

Box PCT
Commissioner of Patents
and Trademarks
Washington, DC 20231

Dear Sir:

Applicant is filing this Preliminary Amendment upon entry into the National Stage of PCT/US00/40921.

No amendment has been made to the claims. Only a sequential numbering problem has been corrected.

In the Claims:

Please cancel claims 1-26 and enter the following new claims.

27. An energy conversion device adapted to enhance field emission, comprising:

a diamond emitter adapted to utilize band bending to emit a high-energy distribution of electrons to produce an energy conversion effect.

28. The energy conversion device of claim 27, the diamond emitter including a geometric tip enhancement.

29. The device of claim 28, the geometric tip enhancement comprising:

micro-nanoscale tips on the cathode emitter.

30. The device of claim 28, the geometric tip enhancement comprising:

a conical tip shape.

31. The device of claim 28, the geometric tip enhancement comprising:

a pyramidal tip shape.

32. The device of claim 28, the geometric tip enhancement comprising:

a hydrogen tip termination.

33. The energy conversion device of claim 27, the diamond emitter including a polycrystalline structure with sp2 bonding.

[redacted]

34. The energy conversion device of claim 27, the diamond emitter including dopants that produce band bending via space charge accumulation.

35. The energy conversion device of claim 27, the dopant selected from a dopant group including as nitrogen, phosphorous, and sulfur-hydrogen.

36. An electronic cooling device, comprising:

a cathode comprising at least one emitter structure on a base; and

an anode positioned over and spaced apart from the cathode by a vacuum space,

a biasing energy supply adapted to bias the cathode to anode separation, the bias of sufficient potential to cause electron emission from the base electrode through the cathode into the conduction band, then through the vacuum and deposition in the anode;

the emitter structure including a diamond microtip emitting portion.

37. The electronic cooling device of claim 36, the diamond microtip emitting portion including a geometric tip enhancement for enhancing band bending.

38. An electronic cooling device, comprising:

a cathode comprising at least one emitter structure on a base, the emitter structure including a diamond microtip emitter extending upwardly from and formed integral to a diamond substrate having a top surface;

an anode layer spaced apart from the emitter and suspended above the diamond substrate by a first insulating layer extending upwardly from the top surface of the diamond substrate;

a porous gate positioned above and spaced apart from the diamond microtip, supported by a second insulating layer extending upwardly from a top surface of the anode layer; and

a biasing energy supply adapted to bias the anode and the gate separation, the bias of sufficient potential to cause electron emission from the base electrode through the cathode into the conduction band, then through the vacuum and deposition in the anode.

39. The device of claim 38, the porous gate is constructed in a grid arrangement.

40. The device of claim 38, the porous gate is constructed in an annular gate structure adapted to provide appropriate electrical conditions for cathode emission, while also providing a path to the anode.

41. The device of claim 38, wherein the bias between the cathode and the anode is maintained at a higher level than that of the bias between the cathode and the gate, but the bias between the cathode and the anode still allows electrons emitted from the cathode to reach the anode.

42. A method for energy conversion using a diamond microtip cathode separated from an anode by a vacuum space, the method comprising:

shifting the field emission band with a positive voltage bias on the anode to narrow the potential barrier width to increase the

probability of quantum tunneling to increase field emission and produce a transfer of thermal energy from the cathode to the anode.

43. The method for energy conversion of claim 42, wherein shifting the field emission band occurs in the cathode.

44. The method for energy conversion of claim 42, the shifting occurring near the base-electrode/cathode interface

45. The method for energy conversion of claim 42, wherein shifting the field emission band occurs in the vacuum.

46. The method for energy conversion of claim 42, the shifting occurring near sp2-bonded elements of the polycrystalline structure.

47. The method for energy conversion of claim 42, the shifting occurring at the cathode/vacuum barrier

48. The method for energy conversion of claim 42, further comprising:

decreasing the resistance to electron flow between the cathode and anode through the use of a gate electrode designed to extract electrons from the cathode while allowing emitted electrons to bypass the gate.

49. An energy conversion structure, comprising:

a biased diamond microtip emitter thermally and electrically connected to a base and spaced from an anode by a vacuum gap, the biased microtip emitter forming curved energy bands adapted to produce a net energy transfer to an anode.

[redacted]

50. The energy conversion structure of claim 49, the net energy transfer manifest as cooling of the base.

51. The energy conversion structure of claim 49, the net energy transfer manifest as power generation with an electrical potential between the anode and the base.

52. A step for improving efficiency for an energy conversion device using a base electrode and a diamond emitter cathode, the step for improvement comprising:

providing geometric enhancement adapted to increase the local electric field at the interface between the base electrode and the diamond cathode.

53. A diamond emitter energy conversion device adapted to provide power to an external circuit, comprising:

a cathode with a microtip structure, the cathode adapted to support a high density of energetic electrons and further adapted to be electrically connected to the external circuit;

an anode spaced from the cathode and adapted to be electrically connected to the external circuit;

an annular gate electrode adapted to provide a low potential field sufficient for emission of electrons from the cathode tip to the anode by bypassing the annular gate; and

a biasing energy supply adapted to bias the anode and the gate separation, the bias of sufficient potential to cause electron emission from the base electrode through the cathode into the conduction band, then through the vacuum and deposition in the anode.

54. A method for increasing efficiency of energy converters utilizing a thermal differential across a structure including a base

connected to a cathode, the cathode separated from an anode by a vacuum space, the cathode including a diamond microtip emitter, comprising:

enhancing band bending potential of the structure during construction of the cathode and anode structure.

55. The method of claim 54, further comprising:

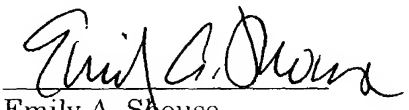
providing a gate electrodes during construction, the gate electrode adapted to reduce the required voltage for field emission within the structure.

REMARKS

Claims 1-26 have been canceled and renumbered as Claims 27-55 to correct a sequential numbering problem. Thus, 29 claims are pending in the application. The claims are otherwise unchanged.

The Commissioner is authorized to charge any deficiency or credit any overpayment associated with the filing of this Preliminary Amendment to Deposit Account 23-0035.

Respectfully submitted,



Emily A. Shouse
Registration No. 44,336
WADDEY & PATTERSON
Bank of America Plaza
414 Union Street, Suite 2020
Nashville, TN 37219
(615) 242-2400

ATTORNEY FOR APPLICANT

DESCRIPTION

THERMODYNAMIC ENERGY CONVERSION DEVICES AND METHODS USING A DIAMOND-BASED ELECTRON EMITTER

TECHNICAL FIELD

The present invention relates generally to energy conversion devices, and more particularly, this invention pertains to the use of diamond-based electron emitters in thermodynamic energy conversion devices.

BACKGROUND ART

The need for efficient, reliable, and cost-effective small-scale energy conversion devices is increasing due to the downsizing of commercial and military products that require either electrical power or compact cooling. An example of a product that requires both of these is a portable infrared detector, which is used for both military and law-enforcement applications. This device requires portable electrical power to drive electronic components as well as a compact cooling system to maintain the temperature of the primary optoelectronic sensor (e.g., a silicon microbolometer) within a narrow range at or below ambient. Similar needs for efficient, small-scale cooling and/or power generation will persist for many future engineering applications.

Small-scale cooling systems are increasingly in demand as the need increases to transfer heat from microelectronic components, such as ultra large scale integration (ULSI) devices and laser diode arrays. The 1997 National Technology Roadmap for Semiconductors indicates that surface cooling rates in excess of 30 W/cm2 will be required for sub-100 nm technology while maximum device junction

temperatures will remain at or below 100°C. Further, the cooling systems must be reliable, inexpensive, and manufacturable.

The required cooling capacity can be achieved by a variety of methods, including single- and two-phase fluid flow, air jet impingement, and both traditional and non-traditional refrigeration schemes. For liquid-flow and air-impingement systems, intricate flow networks and flow-generating mechanisms are required which can limit their practicality. Alternative devices, such as thermoelectric refrigerators, eliminate moving parts by using electrical current to produce refrigeration. However, room-temperature thermoelectric refrigerators are inefficient, with typical coefficients of performance (COPs) that are about one-third those of ordinary vapor-compression refrigerators. Contemporary research is seeking to improve the efficiency of thermoelectrics.

Recently, several researchers have suggested that, in theory, high-efficiency room-temperature refrigeration can be achieved via small-scale electron emission devices. The physical principle of this concept involves thermionic electron emission, whereby hot electrons are ejected over a potential barrier. The primary challenges in achieving thermionic refrigeration involve finding materials with low potential barriers (i.e., work functions) and minimizing reverse heat transfer.

Field emission provides an alternate means of electron emission whereby electrons tunnel through a potential barrier. Field emission is particularly appealing because electrical current densities can be significantly larger than those generated by thermionic emission. This extremely high electrical current density suggests that high thermal current densities are possible. Recent work by several groups suggests that, in theory, field emission devices made from wide-bandgap semiconductors can provide direct cooling.

In addition to cooling applications, compact sources of electrical power (thermal-to-electrical power generation devices) are needed to drive a wide variety of current and future engineering devices. For many applications, electrochemical batteries do not provide sufficient power or energy storage capacity. Other power sources, such as liquid fuels and radioactive elements, possess high energy density but require a means of converting thermal power to electrical form. Like compact cooling systems, the minimization of moving parts is essential to the creation of a new generation of small-scale power generation devices.

Compact thermoelectric and thermionic systems can reliably convert thermal to electrical energy with no moving parts. Several United States patent are directed towards these devices including: United States Patent No. 6,103,298, issued to Edelson et al., on Aug. 15, 2000; United States Patent No. 6,064,137, issued to Cox, on May 16, 2000; United States Patent No. 6,055,815, issued to Peterson, on May 2, 2000; United States Patent No. 6,039,471, issued to Wyland, on March 21, 2000; United States Patent No. 5994638, issued to Edelson, on Nov. 30, 1999; United States Patent No. 5,984,752, issued to Tanaka et al. on Nov. 16, 1999; United States Patent No. 5,981,071, issued to Cox, on Nov. 9, 1999; United States Patent No. 5,874,039, issued to Edelson, on Feb. 23, 1999; United States Patent No. 5,777,427, issued to Tanaka et al., on July 8, 1998; United States Patent No. 5,722,242, issued to Edelson, on Mar. 3, 1998; United States Patent No. 5,712,448, issued to Vandersande et al., on January 27, 1998; and United States Patent No. 5,675,972, issued to Edelson, on Oct. 14, 1997. These patents are hereby incorporated by reference. However, as described previously, these systems are susceptible to low efficiency and materials limitations.

What is needed, then, is an improved method for field emission energy conversion which offers the possibility of improved power densities and high thermal efficiency as compared to competing approaches, and an improved method for field emission as a mechanism for power generation.

DISCLOSURE OF THE INVENTION

The present invention describes specific features that enable or enhance direct energy conversion for uses such as cooling and power generation. The central element of the present invention involves the issue of energy-band bending that enables the selective emission of high-energy electrons.

The preferred embodiments teaches the use of band bending to enable or enhance energy conversion. Three different band bending methods are described. The first involves the use of geometric tip enhancement. The second involves the inclusion of graphite-like (sp2-bonded) molecular structures within the polycrystalline film. These two features produce band bending via small geometric features, such as tips and filaments, as governed by electrostatic theory. The third involves the incorporation of p- and n-type dopants that produce band bending via space charge accumulation.

Fig. 1a shows band diagrams for field emission from diamond cathodes in an unbiased state at thermal equilibrium.

Fig. 1b shows band diagrams for field emission from diamond cathodes under bias with tunneling into and from the conduction band.

Fig. 2 shows a closer view of a field emission process with and without band bending.

Fig. 3 shows refrigeration enhancement using a gate electrode with a band diagram for field emission from a gated diamond cathode in the biased state.

Fig. 4 shows an annular gate structure surrounding a diamond-tip emitter cathode.

Fig. 5 shows a band diagram for a gated power generation device.

Fig. 6 shows a schematic of a direct refrigeration device.

Fig. 7 shows a predicted cooling capacity as a function of applied electric field, field enhancement factor β, and temperature.

Fig. 8 shows a schematic of a direct power generation device.

Fig. 9 shows a predicted thermal efficiency of standalone power generation by field emission as a function of hot-side temperature.

Fig. 10 shows a predicted thermal efficiency of topping cycle power generation by field emission as a function of hot-side temperature.

BEST MODE FOR CARRYING OUT THE INVENTION

The present invention teaches the manipulation of potential barriers, e.g., band bending, to produce enhanced field emission for the purpose of energy conversion. A grid arrangement is also taught for enhanced field emission. In contrast to the prior art teachings regarding thermionic emission over a potential barrier, the present invention utilizes field emission, which involves quantum tunneling through a potential barrier. The basic understanding for the patterned and designed methods for construction of the integral, common and monolithic substrate and emission cathodes for the present invention are taught in the prior incorporated applications. These prior teachings include uniform tip shape, length, grain size, sp2 control, p doping and n doping. It is assumed that the reader has read and understands the basis of those references in the following teachings of the present invention. The present invention builds upon

these teachings by teaching methods for band bending to provide for direct refrigeration and electrical power generation.

Three mechanisms may be used to encourage band bending to enable or enhance energy conversion. The first involves the use of geometric tip enhancement, an example is shown in Figure 3. The second involves the inclusion of graphite-like (sp2-bonded) molecular structures within the polycrystalline film. These two features produce band bending via small geometric features, such as tips and filaments, as governed by electrostatic theory. The third involves the incorporation of p- and n-type dopants that produce band bending via space charge accumulation. Considerations are directed to diamond emitters that preferentially emit a high-energy distribution of electrons to produce an energy conversion effect.

The origin of the tunneling electrons can be the valence band or conduction band depending on geometric and material properties. Emission has been shown to originate from the diamond's valence band in studies on single-crystal diamond and tetrahedral amorphous carbon. However, some forms of polycrystalline diamond grown by chemical vapor deposition emit electrons from the conduction band, aided by a high content of graphite-like (so-called sp2) bonding.

Tunneling into the conduction band is shown schematically in the band diagrams of Fig. 1 for field emission from diamond cathodes. Fig. 1(a) shows the unbiased state, with slight band bending due to space charge effects. E_C is the conduction band energy, E_V is the valence band energy. The band gap, $E_g = E_C - E_V$, of diamond is 5.5 eV, and the difference between the base electrode's Fermi energy and the cathode's valence band energy is typically $E_{FB} - E_V = 1.4$ eV, which is the energy associated with grain boundaries. Cathode doping, such as nitrogen, phosphorous, sulfur-hydrogen, and others, can alter this energy difference. The effective work function ϕ_{eff} is dictated by the

vacuum energy level, E_{vac}. This work function represents the electron energy required to exceed all potential barriers. The parameter $\chi = E_{vac} - E_C$ is the electron affinity and represents the energy required to eject an electron from the conduction band into vacuum. Numerous recent studies indicate that χ is negative when the diamond surface is terminated by hydrogen, although it is shown positive in Fig. 1. This negative electron affinity can significantly enhance emission.

An applied bias may be placed between the base electrode and the anode or the anode and the gate in a gated structure. At sufficiently high biases, the electrons will emit from the base electrode through the cathode into the conduction band, then through the vacuum and deposit in the anode. Note that tunneling may also occur through the barrier between the cathode and the vacuum. By comparing the band diagrams of figure 1(a) and 1(b) one can note that band bending allows for thus use of lower vacuum requirements that required in the prior art.

Under a voltage bias, positive on the anode, the electric field causes the bands in the cathode and vacuum to shift, as shown in Fig. 1(b). Near the base-electrode/cathode interface or near sp2-bonded elements of the polycrystalline structure, significant band bending narrows the potential barrier width w. This narrow barrier increases the probability of quantum tunneling, and field emission occurs. A second tunneling process may also occur at the cathode/vacuum barrier for $\chi>0$. Note that the average energy exchange, ϕ_{ave}, of tunneled electrons can be positive relative to the base electrode's Fermi level due to the triangular-like shape of the barrier. Emitted electrons originate from the high-energy tail of the Fermi-Dirac electron distribution at non-zero absolute temperatures and are transported quasi-ballistically through the cathode into vacuum. In effect, only high-energy electrons are emitted, and the electrical

current caused by this preferential emission produces a commensurate transfer of thermal energy from the cathode to the anode.

Figure 1(b) shows a biased emitter with curved energy bands. A closer view of a field emission process with and without band bending appears in Figure 2. Figure 2 shows two emission processes that, by assumption, produce the same electrical current flows. Despite the fact that the electrical current flows of the two devices are equal, the average energy of electrons emitted through the curved barrier is higher than that of the linear barrier. Prior art devices presume a linear energy barrier, as evidenced by their use of a traditional Fowler-Nordheim equation. Emitted electrons must be replaced by an equal number of electrons to preserve charge continuity. However, in the present invention, these replacement electrons have energies below the average energy of emitted electrons. The replacement energy will, on average, be near the incident energy level, e.g., the Fermi energy of a metal. Thus, the emission process produces a net energy transfer that can be manifest as cooling or power generation.

The physics of field emission have been described in detail by Good and Muller and more recently by Chung et al. The development below provides some of the major results that are central to the present invention. The emission current density J_E takes the form:

$$J_E = \frac{4\pi me}{h^3} \int_0^\infty \int_0^E f(E) D(E_x) dE_x dE \qquad (1)$$

where h is Planck's constant, m is the electron rest mass, f is the Fermi-Dirac energy distribution, and D is the quantum tunneling transmission coefficient. As described by Muller and Good, the transmission coefficient $D(E_x)$ is based on an expansion of the quantum tunneling probability, including the effects of the electrode-

semiconductor work function ($f = V_0 - E_{FB}$), the local electric field F_{local} at the interface, and an image charge potential.

To characterize thermodynamic transport, the average energies of emitted electrons (E_{ave}), as well as those that replace them (E_R) must be known. The difference between the two is the electron exchange energy, $f_{ave} = E_{ave} - E_R$. The average energy of emitted electrons can be calculated by taking an energy moment of Eq. (1)

$$E_{ave} = \frac{\int_0^{\infty}\int_0^{E} Ef(E)D(E_x)dE_x dE}{\int_0^{\infty}\int_0^{E} f(E)D(E_x)dE_x dE} \qquad (2)$$

As proposed by Chung et al., the average energy of the replacement electrons can be calculated as

$$E_R = \frac{\int_0^{E_F}\int_0^{E} E(1-f(E)+f(E)D(E_x))dE_x dE}{\int_0^{E_F}\int_0^{E} (1-f(E)+f(E)D(E_x))dE_x dE}$$

(3)

The energy of replacement electrons typically falls in the range of 0.1 to 0.2 eV below the Fermi level. This result is extremely important in assessing the possibility of direct cooling by field emission, as even emission from slightly below the Fermi level can produce a refrigeration effect when the average replacement energy is below the Fermi level.

Equations (3) and (4) are used to compute the average exchange energy $f_{ave} = E_{ave} - E_R$. The net thermal energy flux of emitted electrons can then be expressed as

$$J_Q = \phi_{ave} J_E$$

(4)

The heat transfer rate described by Eq. (4) flows from the base electrode, through the cathode and vacuum, and finally to the anode.

The term F_{local} represents the local electric field at the interface between the base electrode and the diamond cathode, see Fig. 1. This field is greater than the average field, denoted by F_{ave}, due to geometric enhancement, e.g., micro-nanoscale tips on the cathode emitter, polycrystalline structure (with sp2 bonding), and cathode doping. The local and average fields are often related by a field enhancement factor β as:

$$F_{local} = \beta F_{ave} \quad . \tag{5}$$

This enhancement factor can be very large due to the influence of the emitter geometry, as well as doping and fabrication. The field enhancement factor can be determined from electrical measurements of applied field F_{ave} and current density J_E.

Direct Refrigeration (Cooling)

The fundamental phenomenon described can produce refrigeration.

The flow of thermal energy J_Q from a lower-temperature cathode to a higher-temperature anode is itself refrigeration. According to the Second Law of Thermodynamics, this process requires the input of energy (power). This 'external' power input is manifest in the biasing of the cathode and anode. The electrical energy input can be calculated as:

$$J_{in} = J_E(E_{FB} - E_{FA}) \tag{6}$$

where the term (E_{FB} - E_{FA}) represents the applied bias, and the term J_E is the electrical current density. The electrical current creates a thermal current density. The refrigeration efficiency (coefficient of

performance, CoP) can be calculated as the ratio of refrigeration power to input power,

$$CoP = J_Q / J_{in} = f_{ave} / (E_{FB} - E_{FA}). \quad (7)$$

The refrigeration coefficient of performance can be enhanced by increasing the average energy of emission f_{ave} and by decreasing the cathode-anode bias (E_{FB} - E_{FA}). While the former is a complicated function that involves quantum tunneling and material properties, the latter can be reduced substantially by the presence of a gate electrode. Such a scenario is shown in the band diagram of Fig. 3, which shows the biased state with three electrodes (base, gate, anode). The gate electrode produces appropriate electrical conditions (e.g., electric fields) to enable emission from the base electrode into the cathode and from the cathode into vacuum. The gate is designed to extract electrons from the cathode while allowing emitted electrons to bypass the gate. Thus, the gate should be porous to allow electrons to proceed to the anode. Fig. 3 shows an annular gate structure that provides appropriate electrical conditions for cathode emission, while also providing a path to the anode. The anode's energy level (EFA) is maintained at a higher level than that of the gate but still allows electrons emitted from the cathode to reach it.

Direct Thermal-to-Electrical Power Generation

The basic elements of the refrigeration device can also be configured to create an electrical power generation device. This part of the invention exclusively involves gated emitters as previously described. All energy conversion field emitters require a decreasing potential field in the direction of emission. This process is inherently energy-consuming. However, this energy consumption can be abated or minimized.

One should consider a hot (T > 300°C, for example) tip cathode with a correspondingly high density of energetic electrons according to the Fermi-Dirac distribution. An annular gate electrode provides a low potential field sufficient for emission of hot electrons from the cathode tip. Electrons emit toward the anode (bypassing the annular gate) with a total angular spread of 20-40° from the tip axis. If the cathode and anode are electrically insulated, the system develops an open circuit bias, which ultimately halts the flow of electrons. If instead the cathode and anode are connected by an external circuit, the flow of electrons will continue, and the device produces electric power.

A band diagram for the proposed device is shown in Fig. 5. As shown in figure 5, hot electrons, bolstered in number by the high temperature of the cathode, are emitted into vacuum with an average potential of ϕ_{ave} above the base electrode's Fermi energy E_{FB}. The cathode tips provide the directional orientation of the electrons toward the anode. Electrons with energies greater than (E_{FA}-E_{FB}+f_A) will surpass the anode's surface barrier and proceed into the anode with a current density J_E. Other electrons will flow into the gate and will constitute a loss. The cathode-to-anode power generated by this mechanism is J_E*(E_{FA}-E_{FB}). To minimize losses to the gate, the average energy of emitted electrons must be high, and the anode work function f_A should be as low as possible. The high average emission energy can be achieved through the combination of the triangular barrier, which is inherent to field emission, and high cathode temperatures, which broaden the Fermi-Dirac electron distribution. Sufficiently low anode work functions (»2 eV) can be achieved through proper material selection.

Preferred Embodiments

Direct Refrigeration

The potential applications for this technology fall into two primary areas--cooling of compact heat sources (e.g., electronic components) and air conditioning/environmental controls. In the former area, the principle advantage is the potential for extremely high cooling densities for high-power, compact electronic devices, such as power diodes and transistors. In the latter area, the principal advantages include the potential for high efficiency, compact size, long-term reliability, and the replacement of traditional air-conditioning and refrigeration systems. In both cases, the cost projections are very favorable when compared to competitive technologies. This concept's potential for high efficiency and elimination of refrigerant fluids would significantly reduce harmful environmental effects, including ozone depletion and greenhouse gas production, that are present in current cooling technology. Fig. 6 shows a schematic of an implementation, with a heat source that is cooled by a field emission device, powered by a direct-current power supply (V). Further enhancement may be implanted through the addition of a gate structure.

Fig. 7 shows predicted field-emission cooling capacities as a function of applied electric field. The parameter β represents the field enhancement factor that enables high emission fluxes at moderate applied fields. β-values of 1300 and 535 have been demonstrated by Vanderbilt's Diamond Technology Group, and a β-value of 2500 is considered to be achievable in the near future. For all levels of field enhancement, cooling capacities greater than 10 W/cm2, and some above 1000 W/cm2, are predicted. Such a level of direct cooling far surpasses competitive technologies, such as thermoelectrics.

The efficiencies (i.e., coefficients of performance) for field-emission refrigeration are predicted to approach 85% of the Carnot efficiencies. Thus, air-conditioning units based on field-emission technology could be operated at Energy Efficiency Ratios (EERs) above 20. This level of performance significantly exceeds that of the best available central air units, which provide EER values of 10-12. Given that cooling and refrigeration systems account for 41% of the energy consumption in residential and commercial buildings in the U.S., this level of efficiency improvement could have substantial impact across many commercial sectors.

The high cooling density offered by this technology could address important applications in electronics cooling, where heat fluxes greater than 100 W/cm2 are projected. Further, the technology could readily be applied to novel air conditioning and heat pump devices. At a conservative cooling rate of 10 W/cm2, a field emission cooling system would require only 0.03 cm2 for each Btu/hr of cooling capacity. A 50,000 Btu/hr heat pump or air conditioning system would require a cooling surface area of only 1,500 cm2 (or 15x15 sq. in.). Thus, a window-sized field emission unit could replace an entire central air conditioning system. Obviously, cooling capacities above 10 W/cm2 would decrease the required area and the associated costs.

Based on its high efficiency, compact size, and competitive cost projections, field-emission technology could create a new paradigm in cooling and refrigeration. Residential and commercial air conditioning could be implemented in an unobtrusive and decentralized manner. With the addition of simple heat exchangers and fans, such as perhaps ceiling fans, window field-emission air conditioners could be installed in compact form factors. The opportunity for individual room temperature control would provide further energy efficiency advantages. In the field of electronics cooling, field-emission coolers

could be tightly integrated with compact electronic packages due to their compact structure and high energy density.

Direct Power Generation

The proposed technology would address several key areas in the development of new power generation technology. A generic schematic of the concept is shown in Fig. 8. A heat source (e.g., coal, natural gas, solar radiation, radioisotope, etc.) provides thermal energy to the cathode. The cathode then emits electrons past the gate structure (not shown) to the anode, producing electrical power through a load. The system could be compact (portable) or large (fixed).

This technology would be well suited for industrial power generation systems. As opposed to coal-fired boiler systems, this technology is ideal for capturing the high-temperature energy content of combustion. This high-temperature capability could, for example, be utilized as a retrofitted topping cycle in a traditional coal-fired boiler. The field emitter arrays would be placed in proximity to high-temperature zones near the region of combustion with a refractory material between the combustion region and the diamond field emitters. These devices would then directly convert the high-temperature heat to dc-electricity, and the waste heat would be delivered to the boiler tubes through an appropriate heat exchanger. This approach would take advantage of the projected high efficiency and capacity of field emission energy conversion over broad temperature ranges.

A crucial facet of the proposed technology is its ability to operate efficiently and robustly over broad temperature ranges. Fig. 9 contains theoretical predictions of the thermal efficiencies of field emission energy converters as a function of hot-side temperature over

the range 500°K to 1500°K. The cold-side temperature is assumed to be 350°K. The upper limit on temperature is due to a material limitation of diamond, which graphitizes above approximately 1500°K. The basis model for the calculations in Fig. 9 includes the effects of thermal losses due to thermal radiation between the hot and cold sides. Figure 9 indicates that the proposed technology maintains high efficiency over broad temperature ranges. The predicted efficiency is approximately 85% of the Carnot efficiency, with slightly lower relative efficiency at high temperatures due to the increased effects of thermal radiation losses. Relative to competitive technologies, the predicted efficiencies compare favorably with coal-fired boilers (efficiency ≈ 40%) and gas-turbine combined cycles (efficiency ≈ 56%) and far exceed those of thermoelectrics (efficiency ≈ 10%).

As a topping cycle, the proposed technology could substantially enhance overall efficiency. Fig. 10 shows projected efficiencies for a field-emission topping cycle operating at a cold-side temperature of 840 degrees K (1050 degrees F). The waste heat would be delivered to a typical steam cycle. Figure 10 indicates topping efficiencies in the range of 14-37%, depending on the hot-side temperature. A topping cycle could be developed as a retrofit to existing boilers or designed directly into new boiler concepts.

The high efficiency over a broad temperature range, as shown in Figs. 9 and 10, suggests that field emission energy conversion technology could be implemented in a variety of ways, including as a stand-alone system, a topping cycle, or a bottoming cycle. The technology is inherently compact, and, in contrast to most alternative technologies, contains no moving parts. Hence, the technology possesses inherent capabilities for retrofit systems or for distributed power generation systems, where field reliability is crucial. The

potential thermal energy sources include coal, natural gas, biomass, fuel cells, radioisotopes, and solar radiation, among others.

Field emission energy conversion systems would be mechanically simple, and consequently, could be highly cost effective. Conservative theoretical predictions of generation capacity fall in the range of 10 to above 100 W/cm2, depending on temperature conditions. It is estimated that functional field emitter arrays could be produced at a cost of $1/cm2 including depreciated capital and recurring fabrication expenses. Thus, the technology could be implemented at a cost of only $10-100/kW-dc.

The total system costs of field-emission power generators will depend on the application. For standalone, distributed power, estimates show that a traditional dc-to-ac power conversion system (including inverters, circuit breakers, etc.) could be implemented at a cost of approximately $280/kW, resulting in a total system cost of $290-380/kW-ac. However, CVD-diamond electronic power conversion components (developed in a parallel research program) could reduce this amount to $40-80/kW. Thus, a standalone, all-diamond power generation and conversion system could be implemented at a cost of $50-180/kW-ac for distributed systems (~10 MW). This cost estimate compares very favorably to competitive technologies, including diesel generators (~$600/kW), gas turbines (~$500/kW), and fuel cells (>$1,000/kW).

The proposed technology could also provide significant financial benefits in the development of new coal-fired boilers that include field-emission topping cycles. Consider a field-emission topping cycle that receives heat at 1400 K (2060 F) operating at an efficiency of htopping = 35% (see Fig. 8), and a combined steam cycle operating at an efficiency of hsteam = 40% between 840 K (1050 F) and 350 K (170 F). The overall efficiency for such a system would be

hoverall = htopping + hsteam(1-htopping) = 61%. This level of efficiency would represent a revolutionary improvement over existing technology.

From a cost perspective, new pulverized coal-fired boilers with modern environmental controls (e.g., scrubbers, selective catalytic reduction systems) can be established at a cost of approximately $900/kW-ac. The cost of the topping cycle and associated power conversion system is estimated to fall in the range of $50-180/kW-ac while increasing efficiency from 40% to 61%. Note that, in this scenario, the steam cycle would produce approximately 43% of the total energy (primarily because it receives only the waste heat from the topping cycle), while the topping cycle would produce 57% of the total energy. Thus, the combined system could be implemented at a cost of C = ($900/kW-steam)*43% + ($50-180/kW-topping)*57% = $415-490/kW-total. The primary reasons for this dramatic reduction in cost are that much smaller steam systems would be required and that the field-emission technology is inherently inexpensive.

Figure 11 shows the design of the proof of concept experiment **1100** as used for the present invention. The device includes a cold plate **1101** thermally coupled to a cathode **1102** spaced from an anode **1104**. The anode **1104** is thermally coupled to a calorimeter **1106** which includes cooling channels **1108**. The cooling channels **1108** are flowably coupled to pipes **1110** which provide water pumped from an adjustable temperature bath and pump **1112**. A voltage potential is applied by a power supply **1114** through electrical connections **1116** to the anode **1104** and the cathode **1102**. The current flow in the electrical connections **1116** is monitored by an ammeter **1118**. A thermocouple **1120** is connected by couplers **1122** to the cold plate **1101**, cathode **1102**, anode **1104**, and calorimeter **1106**. The cold plate **1101**, cathode **1102**, anode **1104**, calorimeter **1106** and

connection portions of the electrical connections **1116** and the couplers **1122** are sealed in a vacuum chamber to provide thermal insulation for measurements and the vacuum between the anode **1104** and cathode **1102**. The calorimeter is made of aluminum for good heat conductivity, and a micropositioner (not shown) is used for the anode **1104** / calorimeter **1106** to reduce the load on the cathode **1102**. The calorimeter **1106** is used to measure Q_h. W is calculated from V (power supply) and I (ammeter). Q_s is computed using $Q_s = Q_h - W$.

Figure 12 shows a simple experiment design **1200** for the concept. The simple experiment includes a cold plate **1202** maintained at 27 degrees C, thermally coupled to a diamond cathode **1204**. The diamond cathode **1204** is spaced from an anode **1206** which is thermally coupled to heat spreaders/radiation surfaces **1208**. The heat spreaders/radiation surfaces may be cooled by a thick wire **1210** thermally coupled to a heat sink **1212** and cooled by a fan **1214**. The anode **1206** and cathode **1204** are electrically connected by electrical connections **1216** such that the anode **1206** and cathode **1204** are biased by a power supply **1218**. A thermocouple/RTD **1220** is connected by couplers **1222** to the heat spreaders/radiation surfaces **1208**. The heat spreaders/radiation surfaces **1208** may be prepared with high emissivity paint and separated by low conductivity spacers.

Figure 13 of the drawings shows the basic device structure **1300**. The device structure **1300** includes a base electrode (e.g. metal) **1302** connected to a cathode (e.g. wide band gap semiconductor) **1304** and spaced by a vacuum gap **1306** from an anode (e.g. metal) **1308**.

Figure 14 shows the cathode detail **1400** with the cathode containing a micro-structured surface **1406** to enhance emission. The micro-structure surface **1406** includes conical or pyramidal tips **1402**.

The gate electrodes **1404** can modulate emission and can reduce the required voltage for emission.

Thus, although there have been described particular embodiments of the present invention of a new and useful Thermodynamic Energy Conversion Devices and Methods Using a Diamond-Based Electron Emitter, it is not intended that such references be construed as limitations upon the scope of this invention except as set forth in the following claims.

CLAIMS

What is claimed is:

1. An energy conversion device adapted to enhance field emission, comprising:

a diamond emitter adapted to utilize band bending to emit a high-energy distribution of electrons to produce an energy conversion effect.

2. The energy conversion device of claim 1, the diamond emitter including a geometric tip enhancement.

3. The device of claim 2, the geometric tip enhancement comprising:

micro-nanoscale tips on the cathode emitter.

4. The device of claim 2, the geometric tip enhancement comprising:

a conical tip shape.

5. The device of claim 2, the geometric tip enhancement comprising:

a pyramidal tip shape.

6. The device of claim 2, the geometric tip enhancement comprising:

a hydrogen tip termination.

7. The energy conversion device of claim 1, the diamond emitter including a polycrystalline structure with sp2 bonding.

8. The energy conversion device of claim 1, the diamond emitter including dopants that produce band bending via space charge accumulation.

9. The energy conversion device of claim 1, the dopant selected from a dopant group including as nitrogen, phosphorous, and sulfur-hydrogen.

10. An electronic cooling device, comprising:

a cathode comprising at least one emitter structure on a base; and

an anode positioned over and spaced apart from the cathode by a vacuum space,

a biasing energy supply adapted to bias the cathode to anode separation, the bias of sufficient potential to cause electron emission from the base electrode through the cathode into the conduction band, then through the vacuum and deposition in the anode;

the emitter structure including a diamond microtip emitting portion.

11. The electronic cooling device of claim 10, the diamond microtip emitting portion including a geometric tip enhancement for enhancing band bending.

12. An electronic cooling device, comprising:

a cathode comprising at least one emitter structure on a base, the emitter structure including a diamond microtip emitter extending upwardly from and formed integral to a diamond substrate having a top surface;

an anode layer spaced apart from the emitter and suspended above the diamond substrate by a first insulating layer extending upwardly from the top surface of the diamond substrate;

a porous gate positioned above and spaced apart from the diamond microtip, supported by a second insulating layer extending upwardly from a top surface of the anode layer; and

a biasing energy supply adapted to bias the anode and the gate separation, the bias of sufficient potential to cause electron emission from the base electrode through the cathode into the conduction band, then through the vacuum and deposition in the anode.

13. The device of claim 12, the porous gate is constructed in a grid arrangement.

14. The device of claim 12, the porous gate is constructed in an annular gate structure adapted to provide appropriate electrical conditions for cathode emission, while also providing a path to the anode.

15. The device of claim 12, wherein the bias between the cathode and the anode is maintained at a higher level than that of the bias between the cathode and the gate, but the bias between the cathode and the anode still allows electrons emitted from the cathode to reach the anode.

16. A method for energy conversion using a diamond microtip cathode separated from an anode by a vacuum space, the method comprising:

shifting the field emission band with a positive voltage bias on the anode to narrow the potential barrier width to increase the

probability of quantum tunneling to increase field emission and produce a transfer of thermal energy from the cathode to the anode.

17. The method for energy conversion of claim 16, wherein shifting the field emission band occurs in the cathode.

18. The method for energy conversion of claim 16, the shifting occurring near the base-electrode/cathode interface

19. The method for energy conversion of claim 16, wherein shifting the field emission band occurs in the vacuum.

20. The method for energy conversion of claim 16, the shifting occurring near sp2-bonded elements of the polycrystalline structure.

21. The method for energy conversion of claim 16, the shifting occurring at the cathode/vacuum barrier

22. The method for energy conversion of claim 16. further comprising:

decreasing the resistance to electron flow between the cathode and anode through the use of a gate electrode designed to extract electrons from the cathode while allowing emitted electrons to bypass the gate.

23. An energy conversion structure, comprising:

a biased diamond microtip emitter thermally and electrically connected to a base and spaced from an anode by a vacuum gap, the biased microtip emitter forming curved energy bands adapted to produce a net energy transfer to an anode.

24. The energy conversion structure of claim 23, the net energy transfer manifest as cooling of the base.

25. The energy conversion structure of claim 23, the net energy transfer manifest as power generation with an electrical potential between the anode and the base.

26. A step for improving efficiency for an energy conversion device using a base electrode and a diamond emitter cathode, the step for improvement comprising:

providing geometric enhancement adapted to increase the local electric field at the interface between the base electrode and the diamond cathode.

22. A diamond emitter energy conversion device adapted to provide power to an external circuit, comprising:

a cathode with a microtip structure, the cathode adapted to support a high density of energetic electrons and further adapted to be electrically connected to the external circuit;

an anode spaced from the cathode and adapted to be electrically connected to the external circuit;

an annular gate electrode adapted to provide a low potential field sufficient for emission of electrons from the cathode tip to the anode by bypassing the annular gate; and

a biasing energy supply adapted to bias the anode and the gate separation, the bias of sufficient potential to cause electron emission from the base electrode through the cathode into the conduction band, then through the vacuum and deposition in the anode.

24. A method for increasing efficiency of energy converters utilizing a thermal differential across a structure including a base connected to a cathode, the cathode separated from an anode by a vacuum space, the cathode including a diamond microtip emitter, comprising:

enhancing band bending potential of the structure during construction of the cathode and anode structure.

25. The method of claim 24, further comprising:

providing a gate electrodes during construction, the gate electrode adapted to reduce the required voltage for field emission within the structure.

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
31 May 2001 (31.05.2001)

PCT

(10) International Publication Number
WO 01/39235 A2

(51) International Patent Classification[7]: H01J

(21) International Application Number: PCT/US00/40921

(22) International Filing Date:
18 September 2000 (18.09.2000)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/154,500 17 September 1999 (17.09.1999) US

(71) Applicant *(for all designated States except US)*: **VANDERBILT UNIVERSITY** [US/US]; Office of Technology Transfer, 405 Kirkland Hall, Nashville, TN 37240 (US).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: **FISHER, Timothy, S.** [US/US]; 2508 Essex Place, Nashville, TN 37212 (US). **STRAUSS, Alvin, M.** [US/US]; 2302 Valley Brook Road, Nashville, TN 37215 (US). **DAVIDSON, Jimmy, Lee** [US/US]; 219 River Oaks Road, Brentwood, TN 37027 (US). **KANG, Weng, Poo** [MY/US]; 1222 Spring Creek Drive, Nashville, TN 37209 (US).

(74) Agent: **SHOUSE, Emily, A.**; Waddey & Patterson, Suite 2020, 414 Union Street, Nations Bank Plaza, Nashville, TN 37219 (US).

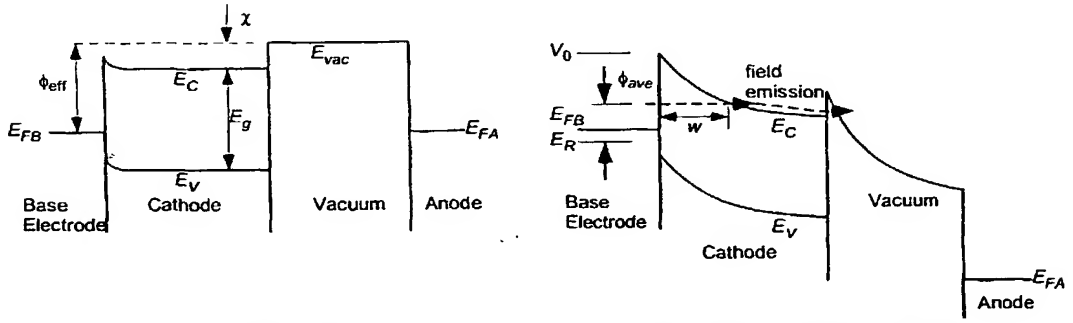
(81) Designated States *(national)*: CN, JP, US.

(84) Designated States *(regional)*: European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published:
— *Without international search report and to be republished upon receipt of that report.*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: THERMODYNAMIC ENERGY CONVERSION DEVICES AND METHODS USING A DIAMOND-BASED ELECTRON EMITTER



(a) at thermal equilibrium

(b) tunneling into and from the conduction band under bias

Band diagrams for field emission from diamond cathodes. (a) Unbiased state. (b) Under bias with tunneling into and from diamond's conduction band.

(57) Abstract: An energy conversion device adapted to enhance field emission including a diamond emitter adapted to utilize band bending to emit a high-energy distribution of electrons to produce an enery conversion effect. The invention teaches the use of band bending to enable or enhance energy conversion. Three different band bending methods are described. The first involves the use of geometric tip enhancement. The second involves the inclusion of graphite-like (sp2-bonded) molecular structures within the polycrystalline film. These two features produce band bending via small geometric features, such as tips and filaments, as governed by electrostatic theory. The third involves the incorporation of p- and n-type dopants that produce band bending via space charge accumulation.

WO 01/39235 A2

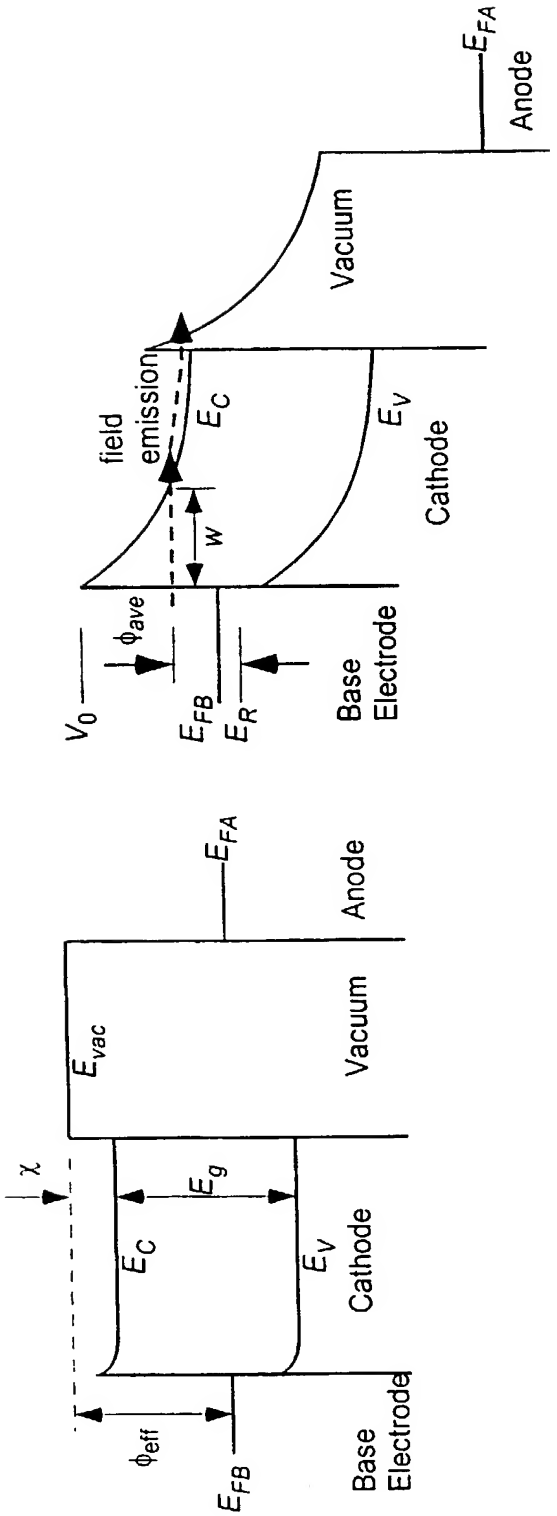


Figure 1. Band diagrams for field emission from diamond cathodes. (a) Unbiased state. (b) Under bias with tunneling into and from diamond's conduction band.

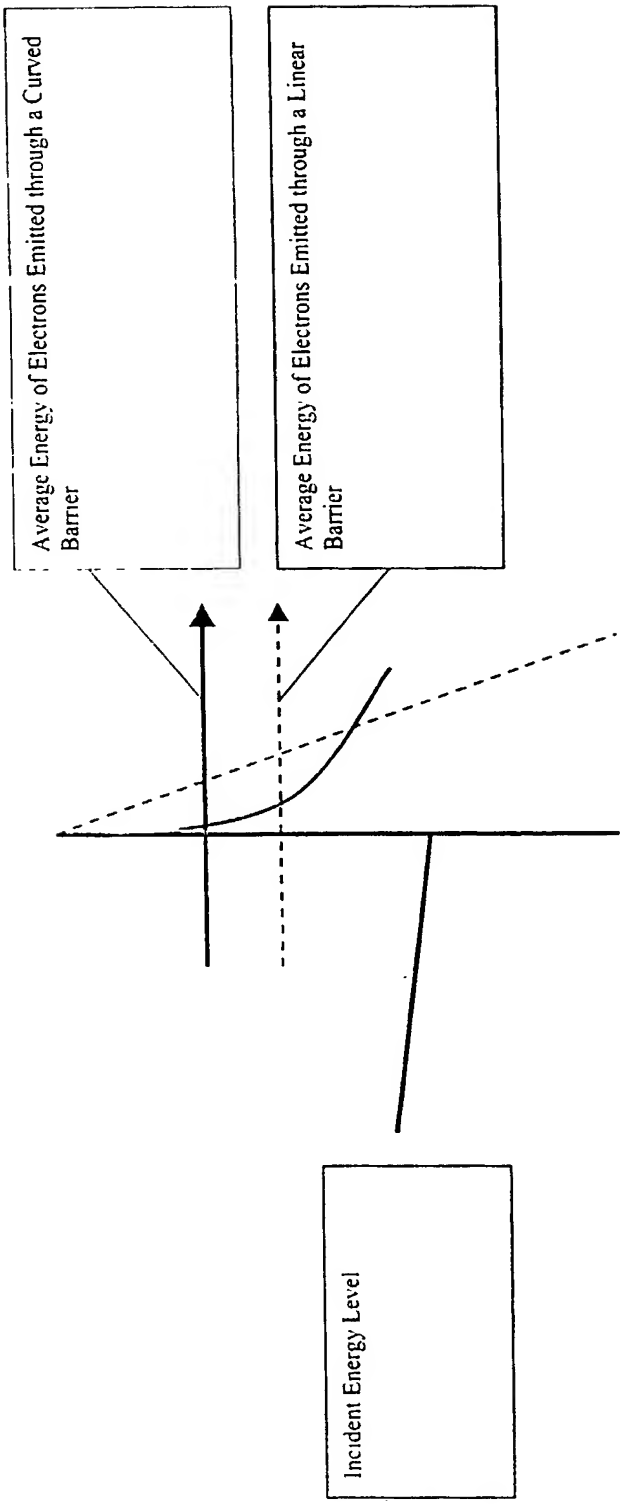


Figure 2. Average electron energies for field emission with and without band bending

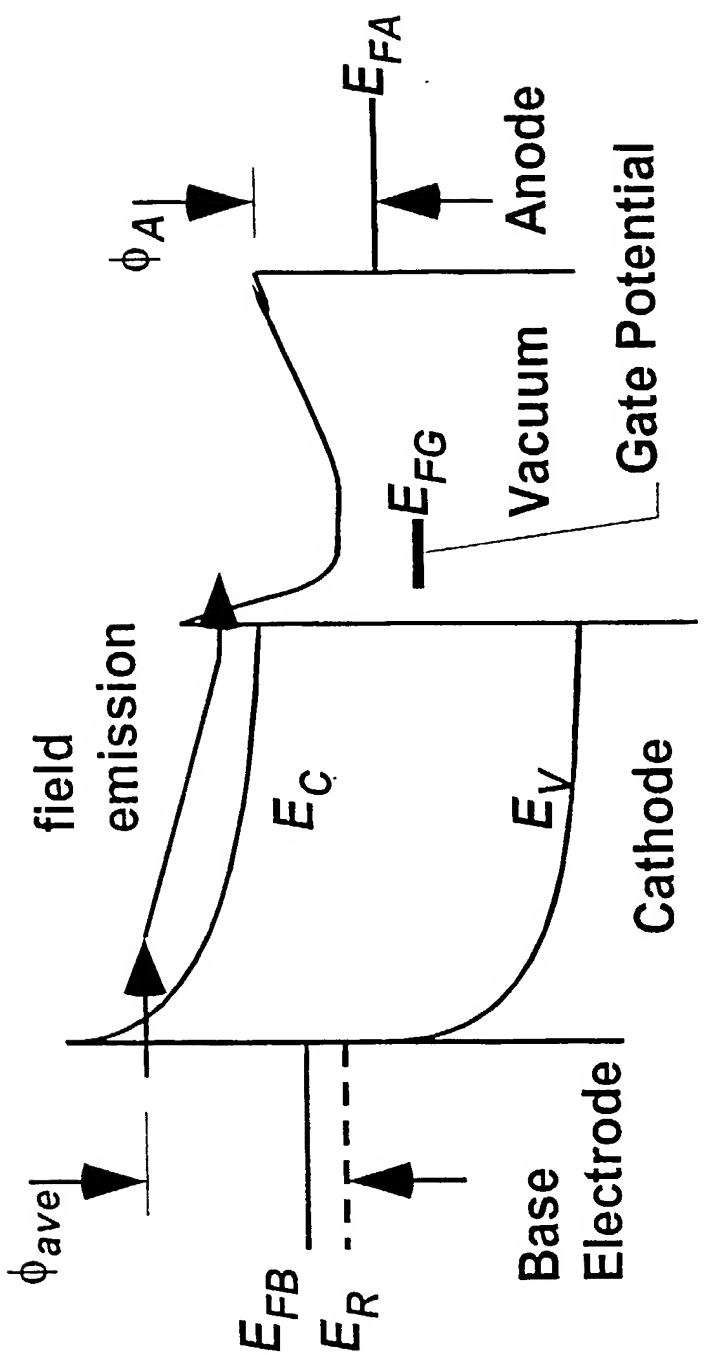


Figure 3. Refrigeration enhancement using a gate electrode. (a) Band diagram for field emission from a gated diamond cathode in the biased state.

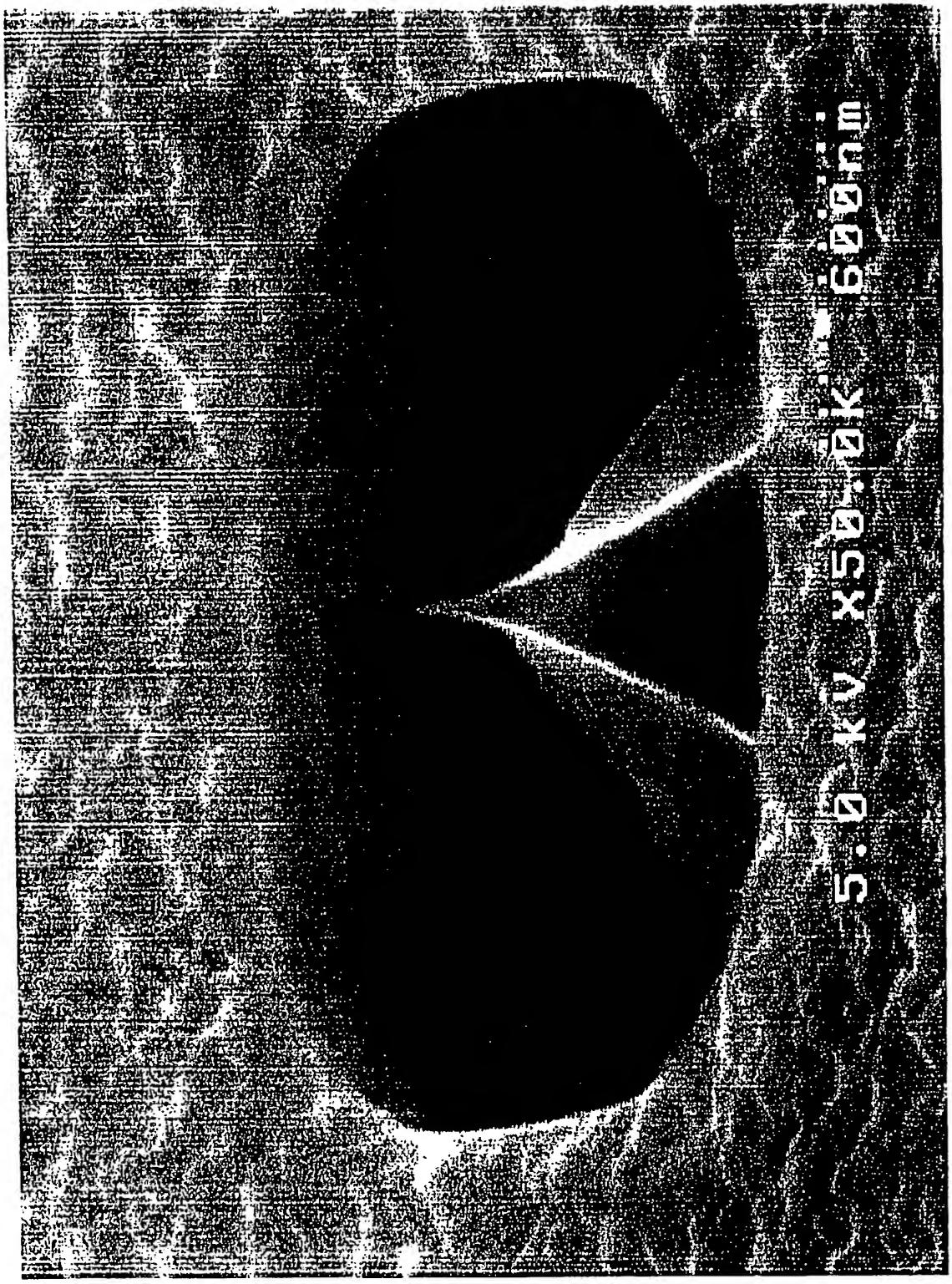


Figure 4. Annular gate structure surrounding a diamond-tip emitter cathode.

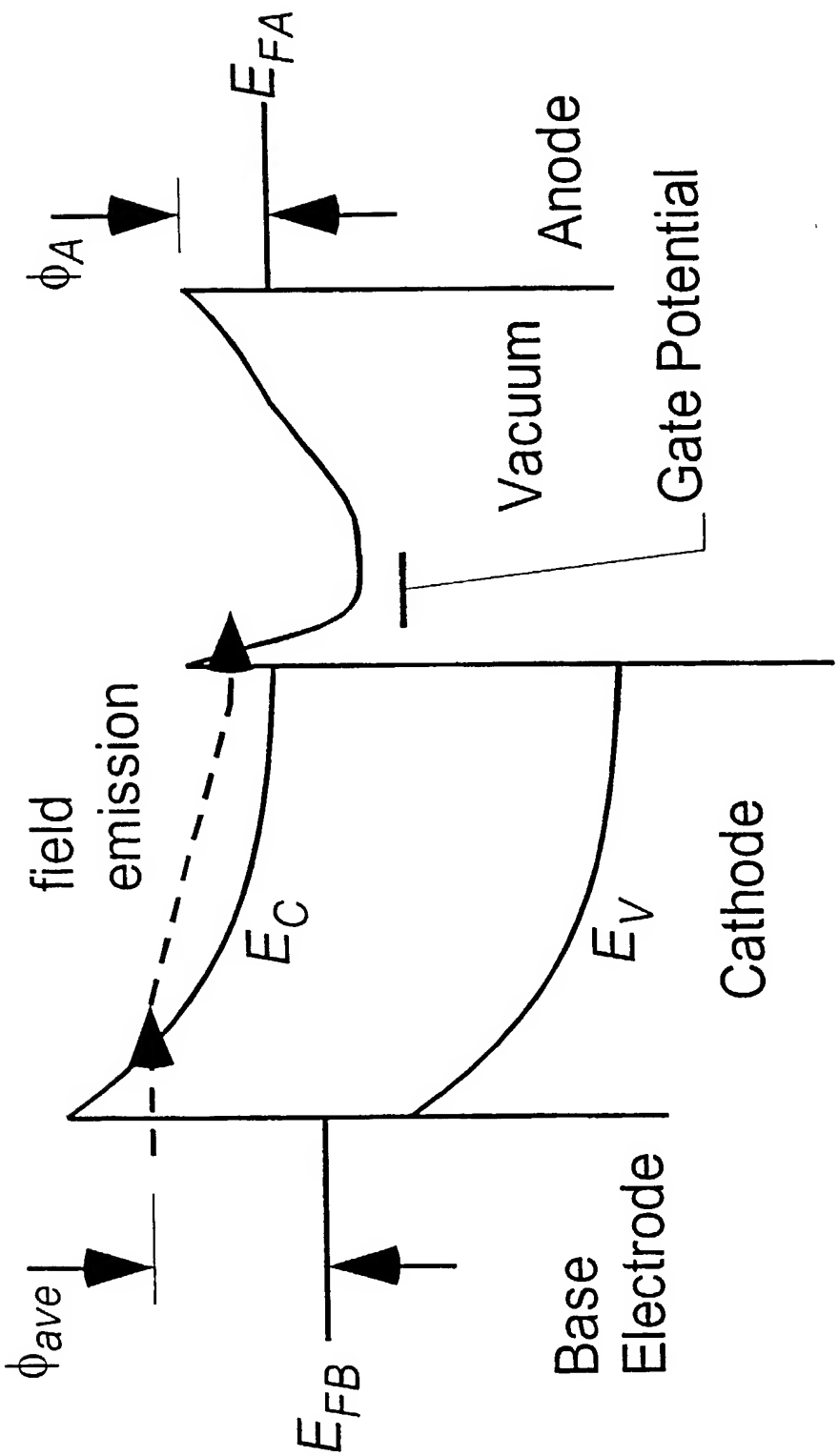


Figure 5. Band diagram for a gated power generation device.

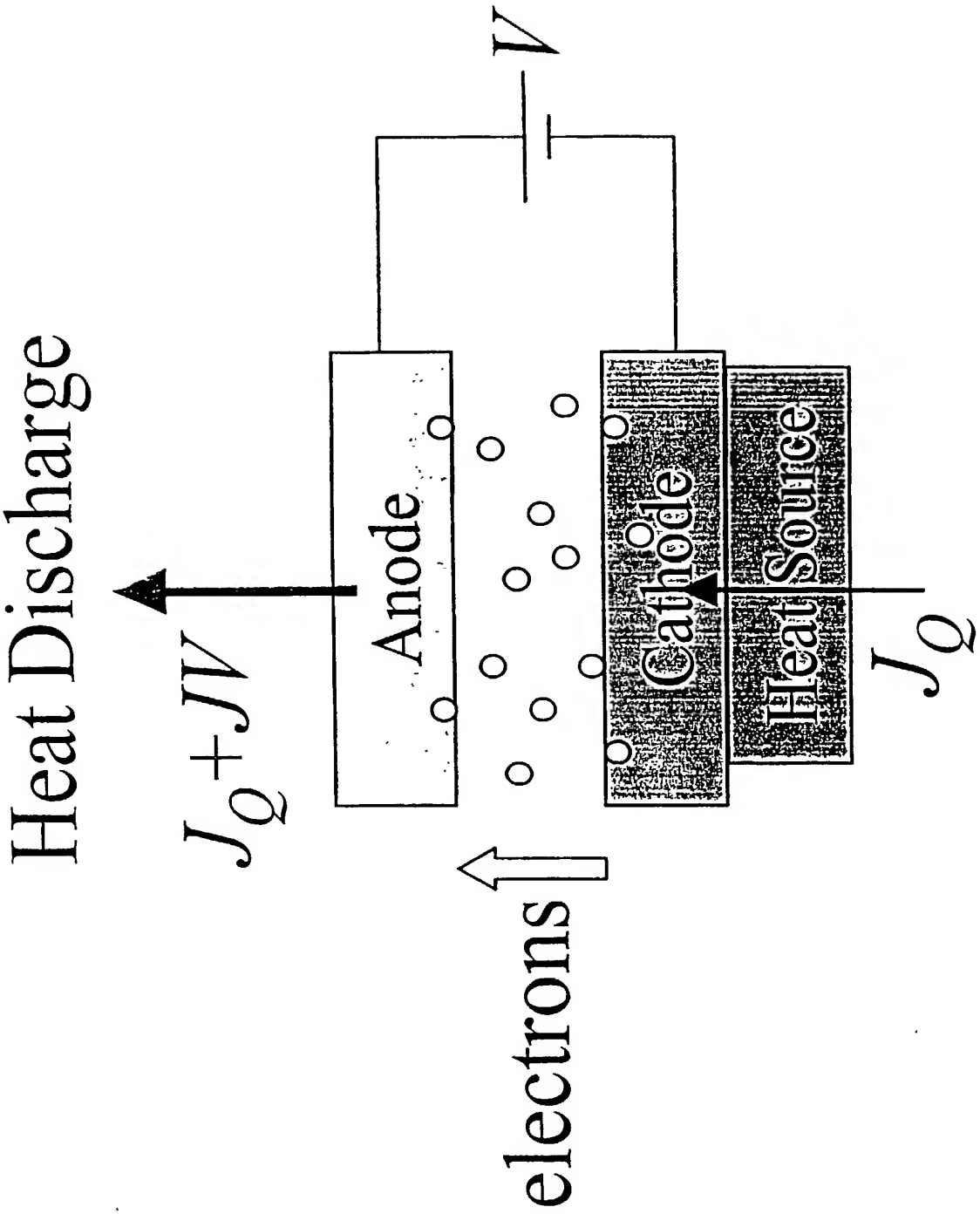


Figure 6. Schematic of a direct refrigeration device.

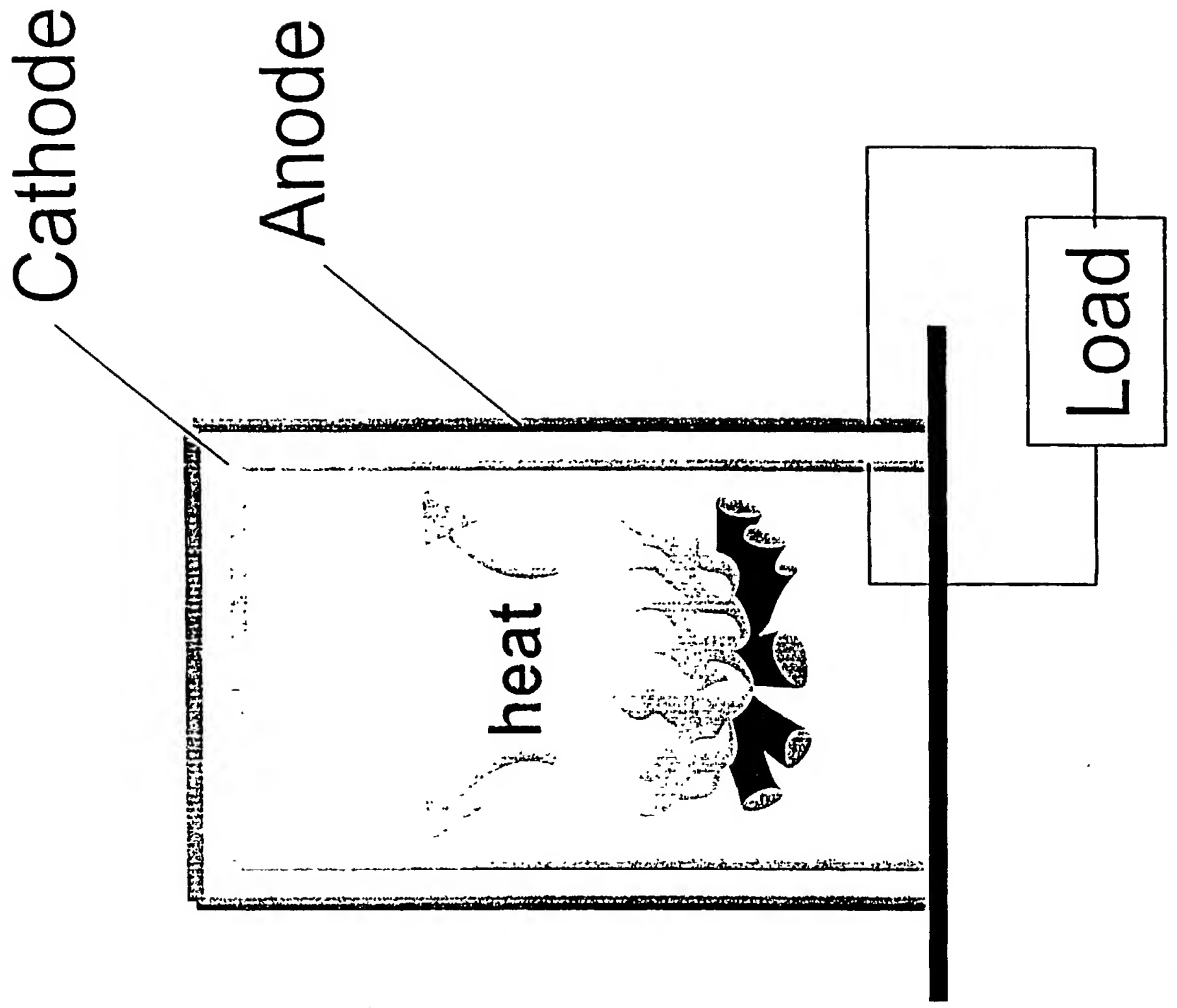


Figure 8. Schematic of a direct power generation device.

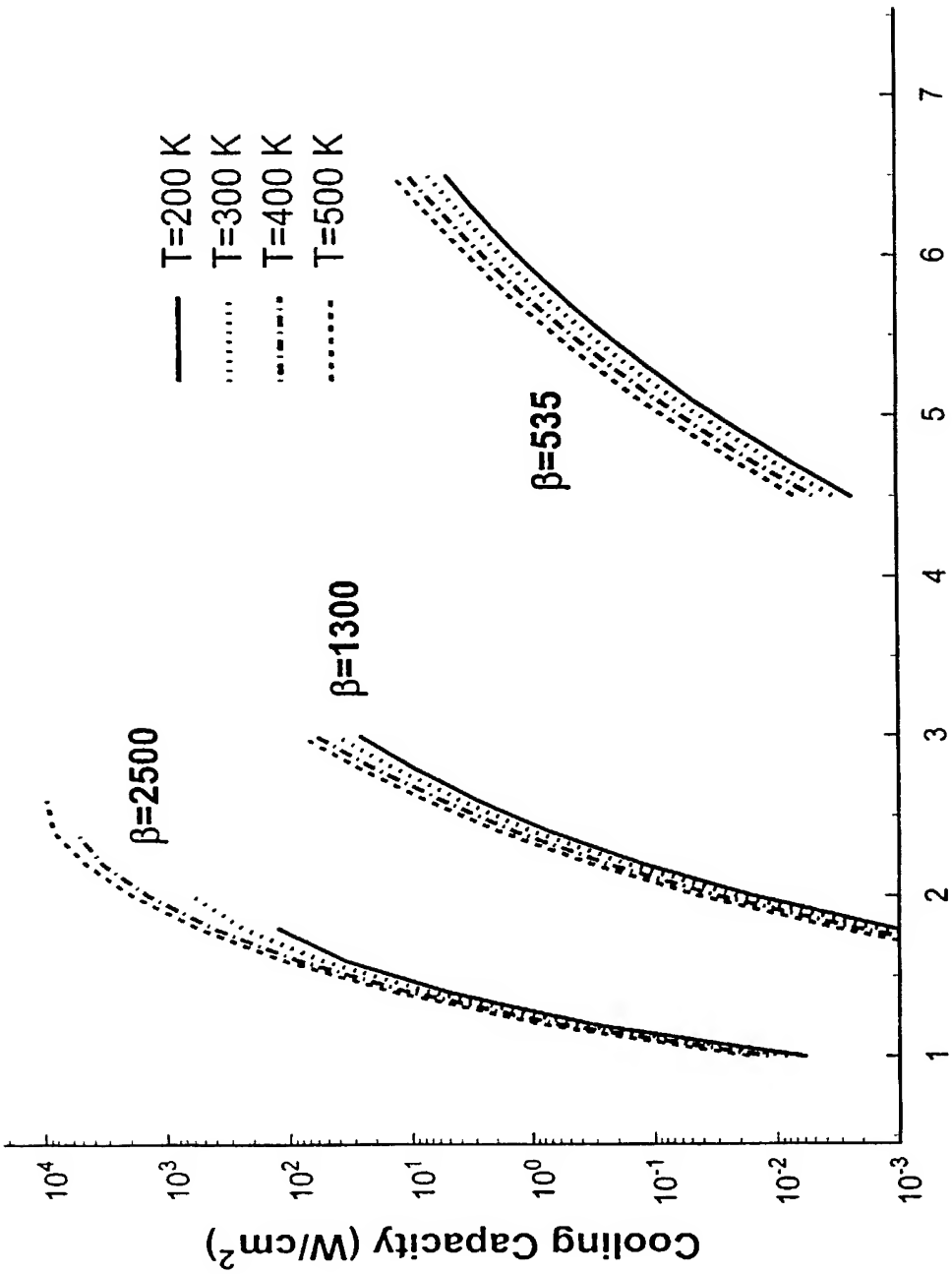


Figure 7. Predicted cooling capacity as a function of applied electric field, field enhancement factor β, and temperature.

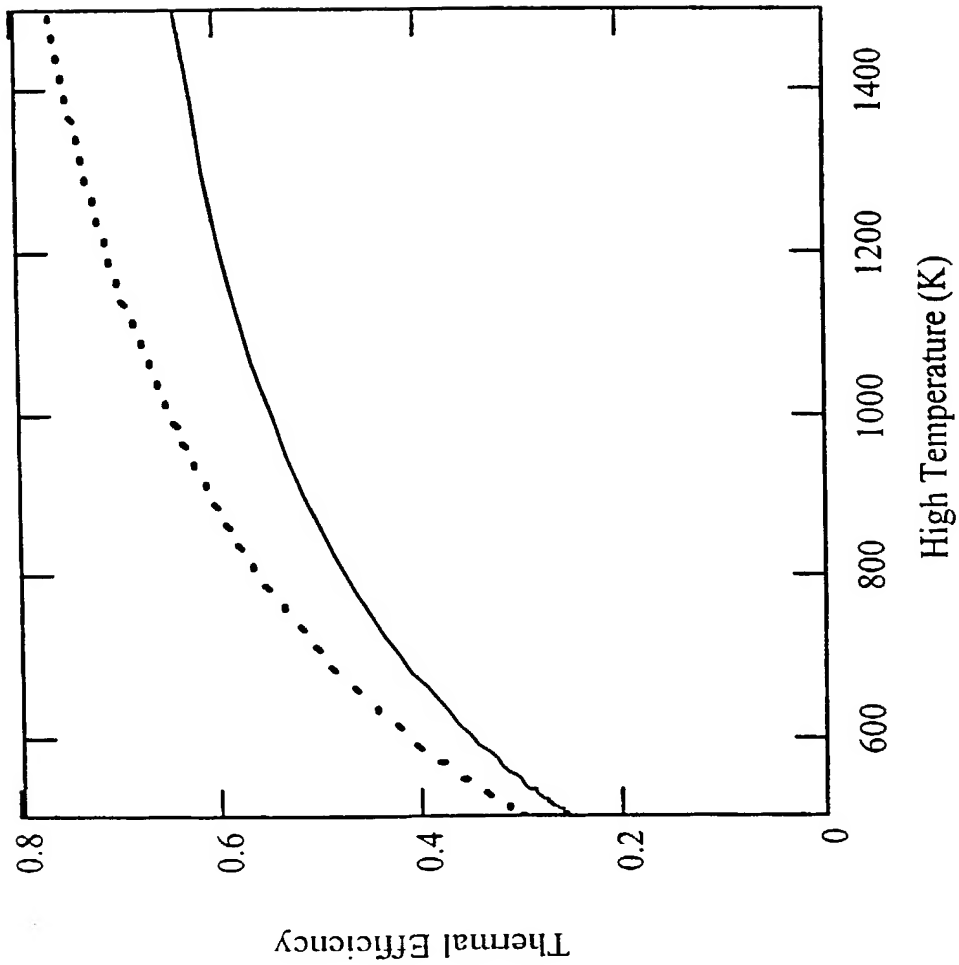


Figure 9. Predicted thermal efficiency of standalone power generation by field emission as a function of hot-side temperature.

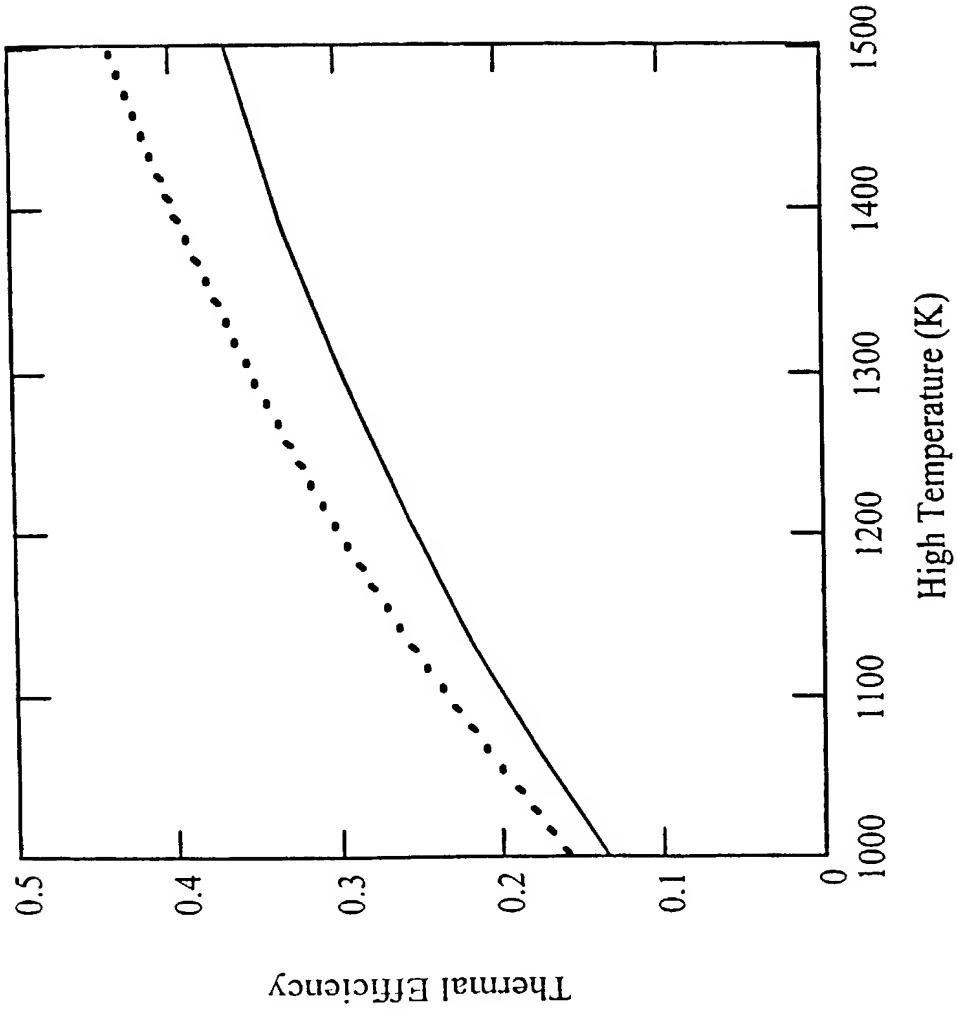


Figure 10. Predicted thermal efficiency of topping cycle power generation by field emission as a function of hot-side temperature.

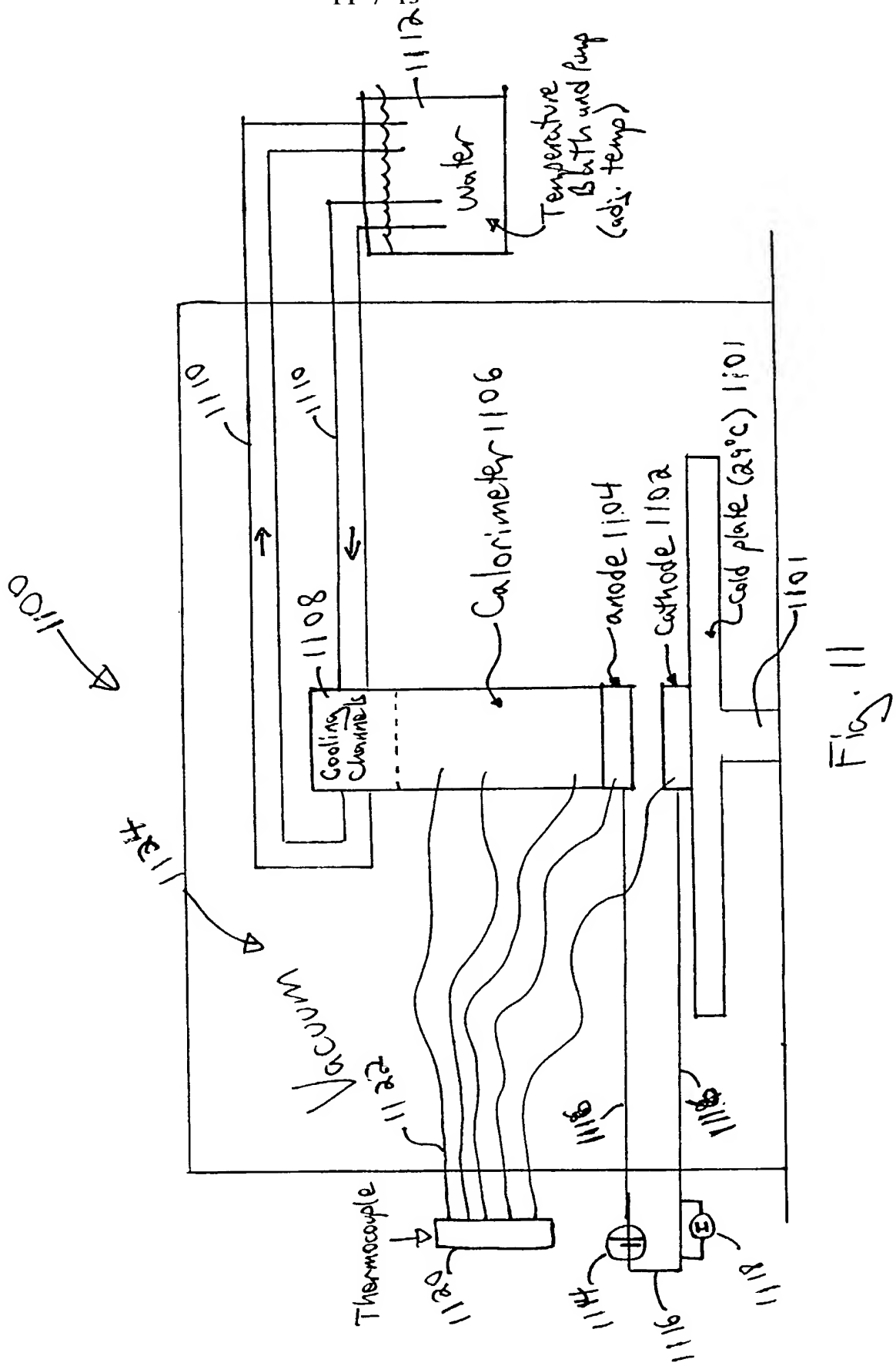

1112
Water
Temperature Bath and Pump (adj. temp)
1110
1111
Calorimeter 1106
1108
Cooling Channels
anode 1104
cathode 1102
Cold plate (29°C) 1101
1100
1134
Vacuum
1128
1126
1126
Thermocouple
1120
1114
1116
1118

Fig. 11

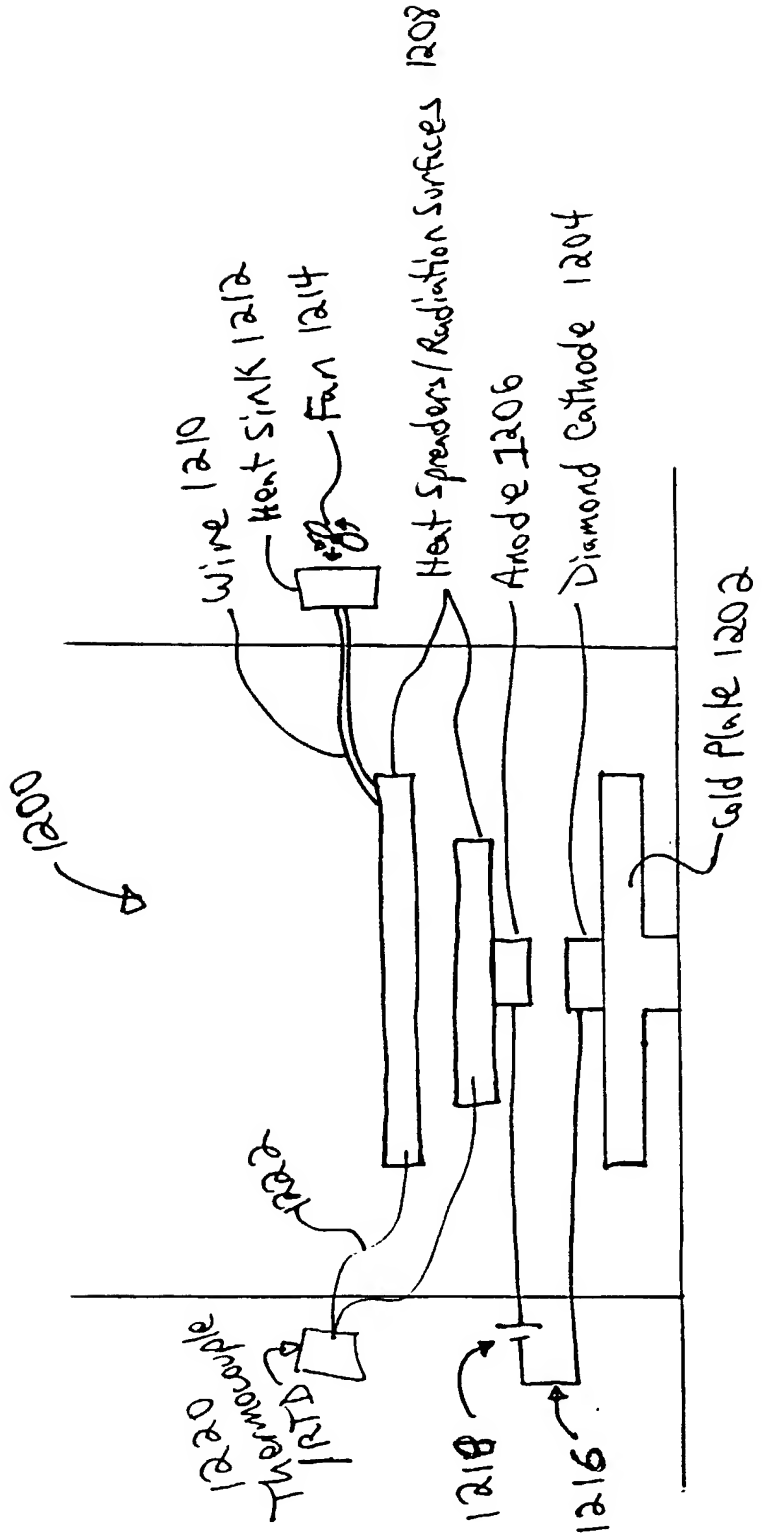

1200
Wire 1210
Heat Sink 1212
Fan 1214
Heat Spreaders/Radiation Surfaces 1208
Anode 1206
Diamond Cathode 1204
Cold Plate 1202
1220
Thermocouple/RTD
1218
1216

Figure 12

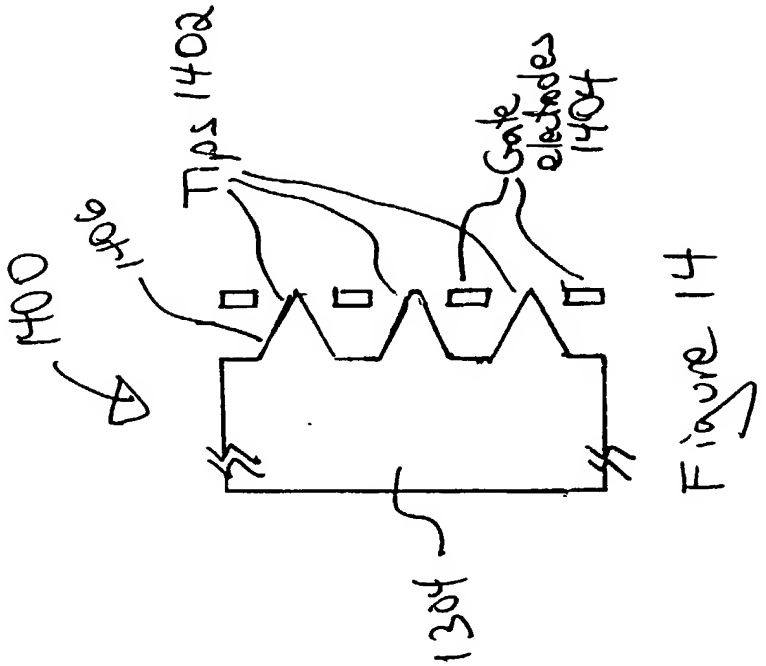


Figure 14

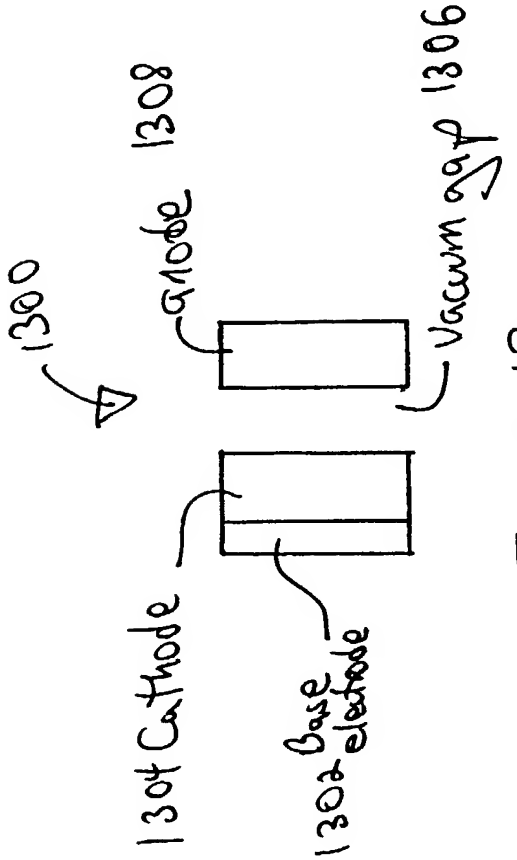


Figure 13

DECLARATION AND POWER OF ATTORNEY

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name.

I believe I am an original, first and joint inventor of the subject matter which is claimed and for which a patent is sought on the invention entitled "Thermodynamic Energy Conversion Devices And Methods Using A Diamond-Based Electron Emitter" the specification of which was filed on 18 September 2000 as PCT International Application Number PCT/US00/40921.

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment specifically referred to above.

I acknowledge the duty to disclose information which is material to patentability as defined in 37 C.F.R. §1.56, including for continuation-in-part applications, material information which became available between the filing date of the prior application and the nation or PCT international filing date of the continuation-in-part application.

I hereby claim foreign priority benefits under 35 U.S.C. §119(a)-(d) or 365(b) of any foreign application(s) for patent or inventor's certificate, or 365(a) of any PCT international application which designated at least one country other than the United States of America, listed below and have also identified below any foreign application for patent or inventor's certificate

having a filing date before that of the application on which priority is claimed:

Prior Foreign Appln. No.	Country	Foreign Filing Date	Priority Not Claimed
PCT/US00/40921		09/18/2000	☐

I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

I hereby appoint the following attorneys and agents to prosecute this application and to transact all business in the Patent and Trademark Office connected therewith:

Mark J. Patterson (Reg. No. 30,412)
I. C. Waddey, Jr. (Reg. No. 25,180)
Edward D. Lanquist, Jr. (Reg. No. 33,729)
Lucian Wayne Beavers (Reg. No. 28,183)
Emily A. Shouse (Reg. No. 44,336)
David B. Pieper (Reg. No. 42,998)
Richard S. Myers, Jr. (Reg. No. 42,022)
Larry W. Brantley (Reg. No. 46,052)
Guy W. Hensley (Reg. No. 41,831)
Douglas W. Schelling (Reg. No. 48,335)

Customer No. 23456

Please direct all correspondence to **Emily A. Shouse** at the address and telephone number below.

Emily A. Shouse
Waddey & Patterson
414 Union Street, Suite 2020
Bank of America Plaza
Nashville, TN 37219
(615) 242-2400

1 -00

Full name of joint Inventor: Timothy S. Fisher

Inventor's signature:

Date: 4/15/02

Residence: 2508 Essex Place TN
Nashville, Tennessee 37212

Citizenship: U.S.

Post Office Address: 2508 Essex Place
Nashville, Tennessee 37212

2 -00

Full name of joint Inventor: Alvin M. Strauss

Inventor's signature:

Date: 4/15/02

Residence: 2302 Valley Brook Road TN
Nashville, Tennessee 37215

Citizenship: U.S.

Post Office Address: 2302 Valley Brook Road
Nashville, Tennessee 37215

3-00

Full name of joint Inventor: Jimmy Lee Davidson

Inventor's signature: Jimmy Lee Davidson

Date: 4-15-02

Residence: 219 River Oaks Road TN
Brentwood, Tennessee 37027

Citizenship: U.S.

Post Office Address: 219 River Oaks Road
Brentwood, Tennessee 37027

4-00

Full name of joint Inventor: Weng Poo Kang

Inventor's signature:

Date: 4-15-02

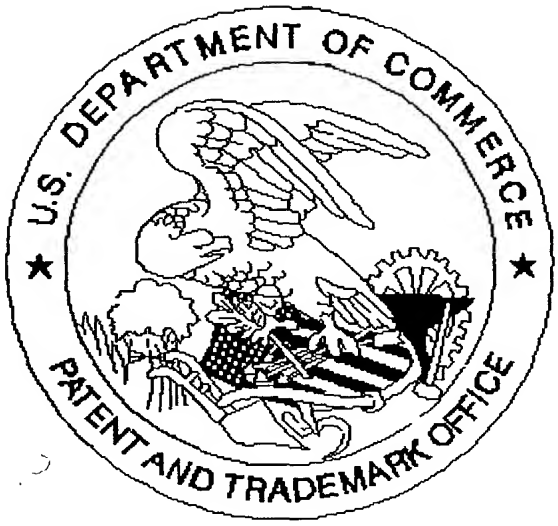
Residence: ~~1222 Spring Creek Drive~~ TN 108 Trace Park Ct. E
~~Nashville, Tennessee 37209~~ Nashville, TN 37221

Citizenship: ~~MY~~ U.S.

Post Office Address: ~~1222 Spring Creek Drive~~ 108 Trace Park Ct. E
~~Nashville, Tennessee 37209~~ Nashville, TN 37221

United States Patent & Trademark Office

Office of Initial Patent Examination -- Scanning Division



Application deficiencies found during scanning:

☐ Page(s)_____ of _____ were not present for scanning. (Document title)

☐ Page(s)_____ of _____ were not present for scanning. (Document title)

☐ ***Scanned copy is best available.*** Some drawings are dark.